Channel Capacity of IM/DD Optical Communication Systems and of ACO-OFDM

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Abstract- **In this paper we investigate the channel capacity of intensity modulated direct detection (IM/DD) wireless optical communication systems for an AWGN channel with a limit on the average transmitted optical power. It has recently been shown that asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) is more efficient in terms of optical power than conventional optical modulation techniques such as pulse position modulation (PPM). When ACO-OFDM is used, the transmitted signal has a clipped Gaussian probability distribution. We calculate the channel capacity for systems using transmitted signals with exponential and clipped Gaussian distributions, and for an ACO-OFDM system. For practical signal to noise ratios, ACO-OFDM has a slightly lower capacity than the other distributions, due to the correlation between samples caused by the ACO-OFDM modulation process. ACO-OFDM has many practical advantages including its tolerance to multipath distortion. This paper shows that it also makes efficient use of the available power and bandwidth.**

Keywords- OFDM; optical communications; intensity modulated direct detection; IM/DD; Channel capacity; Asymmetrically clipped optical OFDM.

I. Introduction

OFDM is used in many new and emerging broadband wired and wireless communication systems because it is an effective solution to intersymbol interference (ISI) caused by multipath transmission or by a dispersive channel [1]. However it has not been used in any commercial optical communication systems. This is because OFDM signals are bipolar, while in optical systems that use intensity modulation (IM), only unipolar signals can be transmitted [2-5]. One way of converting the bipolar signal to unipolar is to add a large DC bias but this results in an optical signal with a high mean optical power [4, 6-10]. This is impractical in the many optical systems in which the average transmitted optical power is limited due to eye safety or other considerations.

Recent research has shown that by asymmetrically clipping particular classes of bipolar OFDM signals, power efficient optical OFDM signals can be derived. ACO-OFDM signals retain the properties that make OFDM resilient in dispersive or multipath channels [11, 12]. It has recently been shown that, surprisingly, in intensity modulated direct detection systems (IM/DD) ACO-OFDM is also more efficient in terms of optical power than on-off keying (OOK) and pulse position modulation (PPM) [13]. OOK and PPM are the types of modulation normally used in IM/DD optical systems. This raises important practical and theoretical questions: What is the limit to performance of IM/DD systems and are there other unknown types of modulation which would give still better performance?

Despite the considerable body of literature on channel capacity for radio systems, there is relatively little relevant literature on channel capacity for IM/DD systems, most of what has been written applies to optical fiber communications, and is not applicable to freespace optics where there are different noise mechanisms. Because the transmitted signals are unipolar and because the power limitation is on $E\{x\}$, rather than $E\{x^2\}$ where x is the transmitted signal, most of the theory and techniques developed for radio and wired communications cannot be used. Hranilovic [4] gives a recent summary of research on channel capacity of optical systems.

In this paper we investigate the channel capacity of IM/DD systems using a system model which is appropriate for wireless optical communication systems. We show that for practical signal to noise ratios (SNR) that a 'clipped Gaussian' distribution is likely to be close to the optimum, capacity achieving distribution. 'Clipped Gaussian' is the probability density function (pdf) of the transmitted signal when ACO-OFDM modulation is used. We also show that the constraints added by the use of ACO-OFDM modulation reduce the capacity slightly. Therefore, as well as being a practical solution to multipath distortion, ACO-OFDM is an efficient modulation technique in an information theoretic sense.

II. System Description

A. Intensity Modulated – Direct Detection (IM/DD) System

Fig. 1 shows the block diagram of the intensity modulated direct detection (IM/DD) optical communication system being considered in this paper. The data is modulated onto an electrical signal, $x_T(t)$. Depending on the details of the electrical system, $x_T(t)$ may be represented by either current or voltage; however in either case the electrical power is proportional to $x_T^2(t)$. The optical intensity modulator generates an optical signal with intensity (not amplitude) $\varsigma x_T(t)$. This means that the optical power is proportional to $x_T(t)$ (not $x_T^2(t)$). It also means that $x_T(t)$ can take only positive values and so modulation techniques commonly used in radio communications cannot be used without modification. The signal is passed through an optical channel with impulse response, $h_c(t)$. The signal $r(t)=h_c(t)\otimes x_T(t)$ is received by a direct detection receiver which converts the optical intensity signal back to an electrical signal (voltage or current). The symbol $\otimes$ represents the convolution operation. We assume that the overall impulse response of the optical to electrical conversion is $h_r(t)$, so that the wanted component of the received signal is given by $h_r(t)\otimes r(t)$.

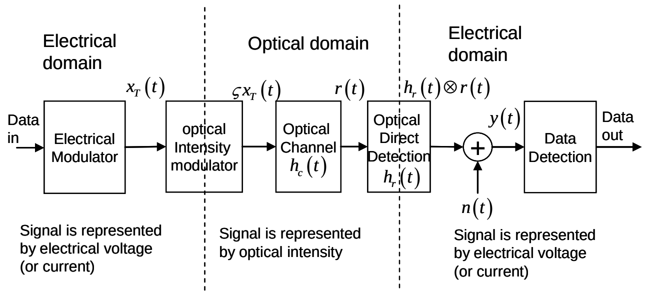

Figure 1. Intensity modulated/direct detection optical communication system

The system model shows additive white Gaussian noise (AWGN) being added in the electrical domain. This is the model commonly used in wireless infrared communication systems [5] where the main impairment is due to high level ambient infrared radiation. The ambient signals are mainly at DC and can be filtered out, however they cause shot noise in the detector, which is accurately modeled as AWGN. The received noisy signal is

$$y(t)=h_r(t)\otimes r(t)+n(t) \tag{1}$$

where $n(t)$ is AWGN. Note that although $r(t)$ is unipolar, $h_r(t)\otimes r(t)$, $n(t)$ and $y(t)$ may be bipolar. The data is recovered from $y(t)$. In this paper we are considering the performance in a flat channel therefore we assume that $\varsigma = h_c(t) = 1$.

In many optical communication systems, the average transmitted optical power $E\{x_T(t)\}$ is constrained by eye safety considerations. This means that the main constraint on signal design is the value of $E\{x_T(t)\}$. This is the situation considered in this paper.

B. Asymmetrically clipped optical OFDM

ACO-OFDM has been described in detail in a number of papers [11, 13]. Here we give a brief outline and highlight only those features of ACO-OFDM which are important in this paper. Fig. 2 shows an ACO-OFDM transmitter and receiver. An ACO-OFDM system is very similar to an OFDM system designed for wired or wireless communications [1]. The data to be transmitted is mapped onto a complex vector, $\mathbf{A}=[A_0 \cdots A_{N-1}]$ of length *N*. The OFDM signal is generated using an *N* point inverse fast Fourier Transform (IFFT). As long as *N* is large enough for the central limit theorem to apply, the real and imaginary outputs of the IFFT have a Gaussian distribution. In the IM/DD system, because the baseband signal is not being used to quadrature modulate a high frequency carrier signal, the output from the IFFT must be real, not complex, so the input to the IFFT, $\mathbf{A}$ is constrained to have Hermitian symmetry. In ACO-OFDM only half of the subcarriers can be used to carry data. A number of forms of ACO-OFDM exist, but in this paper we consider a system where only odd frequency subcarriers are used to carry data [11]. So the input to the IFFT is a complex vector $A_1, A_3 \cdots A_{N-1}$ which has Hermitian symmetry, The even frequency inputs are set to zero, $A_0, A_2 \cdots A_{N-2} = 0$. This results in a bipolar IFFT output vector, $a_0,\cdots a_{N-1}$ To convert to a unipolar form suitable for transmission over a IM/DD channel, the transmitter simply clips all the negative going signals at zero. It can be shown that, if only the odd subcarriers are modulated, the effect of clipping is to reduce the amplitude of all the odd subcarriers by half and to cause intermodulation distortion which falls on the even subcarriers only [11]. After clipping, the odd subcarriers make up half of the total electrical power, the other half of the power is distributed among the even subcarriers, including the zero-th (DC) term. Before clipping the distribution of signal samples is Gaussian, after clipping the signal has a 'clipped Gaussian' distribution. The signal samples are zero with probability 0.5 and otherwise have a half Gaussian distribution.

The samples are then converted to analog and filtered to generate a signal suitable for transmission over the optical channel. At the receiver the signal is demodulated using an *N* point FFT. The even subcarriers are discarded. In the absence of noise and distortion, $B_1 = A_1/2, B_3 = A_3/2, \cdots$.and the transmitted data can be recovered exactly.

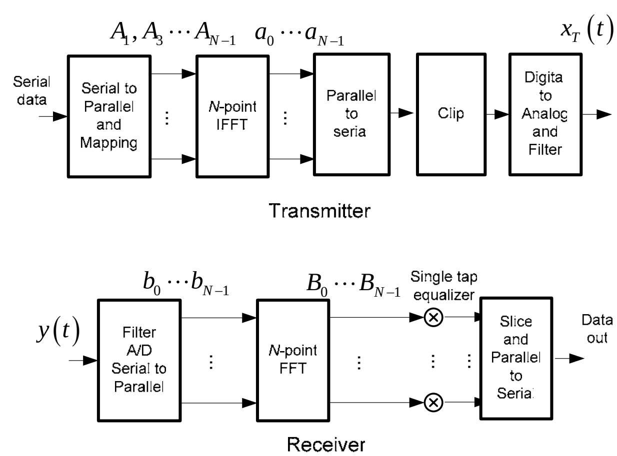

Figure 2. ACO-OFDM transmitter and receiver.

C. System model for channel capacity analysis

Because the signals in an IM/DD system are unipolar, the techniques used in most analyses of the channel capacity of bipolar systems cannot be applied. A bandlimited bipolar system can be represented by samples taken at the Nyquist rate, and every possible sequence of bipolar samples can be converted to a bipolar continuous signal by using an ideal low pass filter. Thus bandlimited bipolar continuous signals can be represented as points in a multidimensional space, where each dimension represents the value of one signal sample. However most sequences of unipolar samples correspond to bipolar (not unipolar) continuous bandlimited signals, so the normal approach cannot be used. One way to avoid this problem is to define the unipolar signals as a superposition of orthogonal basis functions over a time period, including a constant (DC) basis function and constrain the amplitudes of these functions so that the continuous signal given by their sum is always positive [14, 15].

We take a different approach. We assume that all, or almost all, of the bandlimiting occurs at the receiver, in the optical to electrical conversion stage, or in the electrical parts of the receiver. This removes the constraint that the continuous bandlimited signal which the signal samples represent must be unipolar. This model is a good representation of many practical optical wireless systems. Even if optical filters are used, the bandwidth of the optical channel is much greater than the bandwidth of practical optical receivers. The channel may be subject to multipath fading, but the use of OFDM means that transmission can still be achieved in a frequency selective channel. If a laser rather than a light emitting diode (LED) is used at the transmitter, the bandwidth of the transmitter will be much greater than the bandwidth of the receiver.

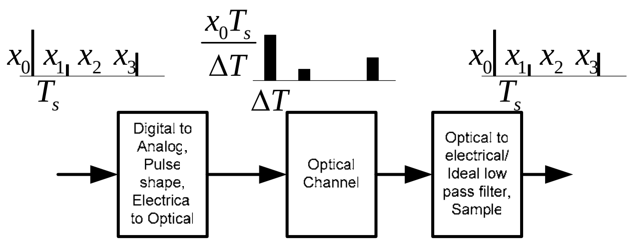

Figure 3. Signal model used in capacity calculations

Fig. 3 shows the signal model that we use in the capacity calculations. Each digital sample, x_m, generated by the digital section of the transmitter is represented in the optical channel as the intensity of a short square pulse. Pulses are transmitted at intervals, T_s. The time duration of each pulse is ΔT, the amplitude of each pulse is $x_m T_s / \Delta T$. By using this scaling we make the average transmitted optical power, P_O, independent of the pulse length and the data rate. It depends only on the pdf of the signal samples

$$E\{x_T(t)\} = P_O = E\{x_m\} = \int_0^\infty x f_x(x)\,dx \tag{2}$$

where $f_x(x)$ is the pdf of the signal samples.

At the receiver the signal is converted from optical to electrical and filtered using an ideal bandpass filter with bandwidth $1/2T_s$. The filtered signal is sampled at the Nyquist rate at the ideal sampling instants. In the absence of noise and distortion and if $\Delta T \to 0$, the received samples will be exactly equal to the transmitted samples.

In practice, the pulses will have finite duration, and the filtering and sampling will not be perfect, but the approximations result in a mathematically tractable model. OFDM is very resilient to the distortions that a real system would introduce, so the results give a realistic estimate of the performance of an IM/DD system using ACO-OFDM.

III. CHANNEL CAPACITY CALCULATIONS

Using the model in Fig. 3 we can consider the system as a discrete time channel with input signal $x(m)$ and output $y(m)$ where

$$y(m) = x(m) + n(m) \tag{3}$$

and $n(m)$ is additive white Gaussian noise. Then the channel capacity is given by

$$\text{C} = \max I(\text{x}, \text{y}) \tag{4}$$

Where $I(x, y)$ is the mutual information and in this case is given by

$$I(\text{x}, \text{y}) = h(y) - h(n) \tag{5}$$

$h(y)$ is the differential entropy of the received signal plus noise and $h(n)$ is the differential entropy of the noise. From the definition of differential entropy

$$h(y) = \int_{-\infty}^{\infty} f_y(y) \log_2\left(f_y(y)\right) dy \tag{6}$$

where $f_y(y)$ is the pdf of the received signal samples. Thus $h(y)$ depends on the pdf of the signal plus noise, which in turn depends on the pdf of the signal. As the noise is Gaussian

$$h(n) = 0.5 \log_2 2\pi 2\sigma_n^2 \tag{7}$$

where σ_n^2 is the variance of the noise [16].

The channel capacity depends on the constraints put on the maximization. If the only constraint is that the average optical power is limited then the maximization is over all probability distributions of the transmitted samples, $f_x(x)$, subject to the constraint

$$P_O = \int_0^\infty x f_x(x)\,dx \le P_{O_{Max}} \tag{8}$$

where $P_{O_{Max}}$ is the maximum allowable mean optical transmit power. Because the noise and the signal have different distributions there is no simple closed form solution to the maximization in (4). Instead we calculate the capacity for two signal distributions: an exponential distribution and the 'clipped Gaussian' distribution which is given by ACO-OFDM We choose the exponential distribution because Shannon showed that if the signal is positive and $E(x)$ is fixed, then the distribution which has the biggest entropy is [16]

$$f_1(x) = \frac{1}{a} e^{-\frac{x}{a}} \qquad (x > 0) \tag{9}$$

and

$$E(x) = \int_0^\infty x f_1(x) dx = a \tag{10}$$

However this does not guarantee the largest channel capacity, as the capacity depends on the distribution of signal *plus* noise, not on the distribution of the signal alone.

The pdf of the clipped-Gaussian distribution is,

$$f_2(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} \qquad (x > 0) \\ P(x = 0) = 0.5 \tag{11}$$

where σ^2 was the variance of the Gaussian distribution *before* clipping.

TABLE I PARAMETER COMPARISON

Distribution	Exponential	Clipped-Gaussian
E(x)	a	$\sigma/\sqrt{2\pi}$
E(x^2)	a^2	$0.5\sigma^2$

Table I shows the relevant parameters of the two distributions. Without loss of generality, we let $E(x) = 1$, i.e. $a = 1$ and $\sigma = \sqrt{2\pi}$. Also $x(t)$ and noise $n(t)$ are independent, therefore, the distribution of the sum is the convolution of the distributions.

$$f(y) = f(x) \otimes f_n(x) \tag{12}$$

We will now calculate the channel capacity for these two distributions and for ACO-OFDM.

Case 1: Exponential distribution

When the signal has an exponential distribution, the distribution of signal plus noise is given by

$$\begin{aligned} f_1(y) &= \int_0^\infty f_1(x) f_n(y-x) dx = \int_0^\infty e^{-x} \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{(y-x)^2}{2\sigma_n^2}} dx \\ &= \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{[x-(y-\sigma_n^2)]^2 + y^2 - (y-\sigma_n^2)^2}{2\sigma_n^2}} dx \\ &= e^{-y} e^{\frac{\sigma_n^2}{2}} \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{[x-(y-\sigma_n^2)]^2}{2N}} dx \\ &= 0.5 e^{-y} e^{\sigma_n^2/2} erfc\left(\frac{-y+\sigma_n^2}{\sqrt{2\sigma_n^2}}\right) \end{aligned} \tag{13}$$

Combining (4), (5), (6) and (7) gives

$$C_1 = -\int_{-\infty}^\infty f_1(y) \log_2 f_1(y) dy - 0.5 \log_2 2\pi 2\sigma_n^2 \tag{14}$$

Using (13) and (14), the distribution was calculated numerically for a range of signal to noise ratios. The results are shown in Fig 4.

Case 2: Clipped Gaussian distribution

To calculate the capacity for the clipped Gaussian distribution, we first derive the pdf for y,

$$f_2(y) = P(x=0) f_y(y|x=0) + P(x \neq 0) f_y(y|x \neq 0) \tag{15}$$

Then, using $P(x=0) = P(x \neq 0) = 0.5$ and the convolution theorem to calculate the sum of independent random variables and

$$\begin{aligned} f_2(y) &= 0.5 f_n(y) + 0.5 \times f_y(y|x \neq 0) \\ &= 0.5 f_n(y) + 0.5 \int_{-\infty}^\infty f_x(x) f_n(y-x) dx \end{aligned} \tag{16}$$

Because $x \geq 0$ we can change the range of the integration so

$$f_2(y) = 0.5 f_n(y) + 0.5 \int_0^\infty f_x(x) f_n(y-x) dx \tag{17}$$

Then substituting the normal distributions for $f_n(y)$, $f_x(x)$ and $f_n(y-x)$

$$f_2(y) = 0.5 \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{y^2}{2\sigma_n^2}} + 0.5 \int_0^\infty \frac{2}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{(y-x)^2}{2\sigma_n^2}} dx \tag{18}$$

Then after some manipulation and using the identity $\mathrm{erfc}(x) = 2/\sqrt{\pi} \int_x^\infty e^{-t^2} dt$ and substituting $\sigma = \sqrt{2\pi}$,we get

$$\begin{aligned} f_2(y) &= 0.5 \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{y^2}{2\sigma_n^2}} + \\ & \frac{1}{\sqrt{8\pi(\sigma_n^2 + 2\pi)}} e^{-\frac{y^2}{4\pi + 2\sigma_n^2}} erfc\left(-\sqrt{\frac{\pi}{\sigma_n^2(2\pi + \sigma_n^2)}} y\right) \end{aligned} \tag{19}$$

This can be used to numerically calculate the capacity for varying SNRs, the results are also shown in Fig 4.

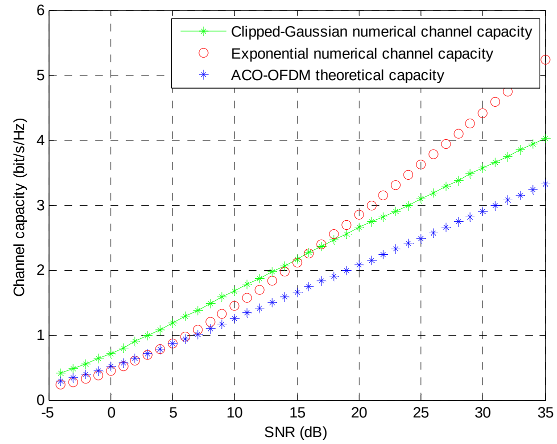

Figure 4. Channel capacities for an optical channel with mean optical power constraint for a clipped Gaussian distribution, an Exponential distribution and ACO-OFDM

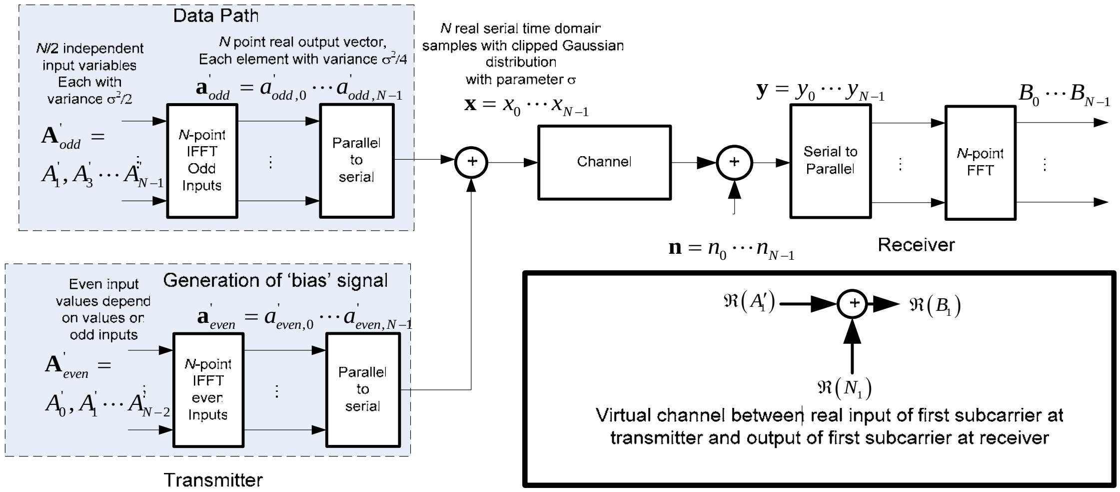

Figure 5 Model explaining the $N/2$ virtual channels formed by the ACO-OFDM system

Case 3: ACO-OFDM

The capacity for the clipped Gaussian signal, gives an upper bound on the capacity of ACO-OFDM but it does not give the actual capacity, because the mapping of subcarriers onto signal samples in ACO-OFDM introduces some correlation between the samples which reduces the capacity. However it is relatively simple to calculate the capacity for ACO-OFDM by simply considering the signals and noise on each of the odd frequency subcarriers. Fig. 5 shows the relationship between the OFDM system and the $N/2$ 'virtual channels' formed by the odd frequency subcarriers. As we noted earlier the effect of clipping is to halve the amplitude of each of the odd subcarrier. All of the intermodulation distortion falls on the even subcarriers. In Fig. 5, the ACO-OFDM transmitter is divided conceptually into the data carrying odd subcarriers, and the even subcarriers which serve simply to ensure that the signal is always positive. Because clipping halves the values of the odd subcarriers, $A_1^{'} = A_1/2, A_3^{'} = A_3/2$ etc. In the absence of noise the odd subcarriers are received without error and $B_1 = A_1^{'}$ The Hermitian constraint and the use of only odd subcarriers means that there are only $N/4$ independent complex inputs, or equivalently $N/2$ independent real/imaginary inputs. When the effect of clipping is taken into account it is easy to show that if these are i.i.d variables and if the variance of each of these is $\sigma^2/2$ then the discrete time output values $x(m)$ have a clipped Gaussian distribution with parameter σ. Thus, from Table 1 for a normalized optical power of unity, $\sigma = \sqrt{2\pi}$. This gives us the signal power for each of the 'virtual channels'.

The noise at the output of the receiver is simply the FFT of the Gaussian noise in the channel, and so it has the same variance. Thus the real/imaginary output of the transmitter IFFT for each of the odd subcarriers is the sum of a signal with variance $\sigma^2/2 = \pi$ and Gaussian noise with variance σ_n^2. The inset in Fig 5 shows that the effect of the channel on the real component of the first subcarrier is simply to add Gaussian noise, $\Re(N_1)$ where $\Re(N_1)$ is the real component on the first subcarrier resulting from the FFT of the time domain noise.

There are no constraints on the complex values carried by each of the odd frequency OFDM subcarriers. We assume that the achieving Gaussian distribution is used. Then the capacity of the system can be readily found by applying the Shannon capacity formula [16] for a bipolar channel subject to the constraint the variance is less than $\sigma^2/2$ and noting that because there are $N/2$ rather than N independent inputs, the effective bandwidth of the channel is halved. This gives

$$C_{ACO-OFDM} = \frac{1}{2}\times\left(\frac{1}{2}\log_2\left(1+\frac{S}{N}\right)\right) = \frac{1}{4}\log_2\left(1+\frac{\frac{\sigma^2}{2}}{\sigma_n^{\ 2}}\right) \quad (20)$$

Applying the optical power constraint and rearranging gives

$$C_{ACO-OFDM} = \frac{1}{4}\log_2\left(1+\frac{\pi}{\sigma_n^{\ 2}}\right) \quad (21)$$

The capacity of ACO-OFDM is also shown in Fig. 4.

IV. Discussions

A. Comparison of the capacities of the systems considered

Fig. 4 shows the capacities, as a function of SNR, of the three systems considered. For SNRs above 15dB, the exponential distribution has the highest channel capacity. This is because at high SNRs the distribution of signal plus noise, is approximately equal to the distribution of the signal alone. As we have already noted, Shannon showed that the exponential signal distribution is the unipolar distribution with the highest entropy when there is a constraint on E{x} [16]. At lower SNRs (<15dB) the effect of noise on the distribution becomes more important and the clipped Gaussian distribution has a higher capacity. As expected the capacity of ACO-OFDM is lowest at all SNRs, because of the extra constraints imposed by the ACO-OFDM mapping of data onto the transmitted signal. However the loss in channel capacity is quite modest at all but the highest SNRs. This is rather surprising because the number of independent dimensions is being halved. In radio or wired systems using bipolar transmission, reduction in the dimensionality of the signal is usually associated with significant loss in capacity. However the use of ACO-OFDM maps $N/2$ bipolar dimensions, onto N unipolar dimensions, so the overall loss in capacity is quite small. The analysis presented has not determined the theoretically optimum capacity, but it is likely that the optimum value is close to the exponential result at high SNRs.

B. Practical Implications of Results

Although there is some small loss in theoretical capacity incurred by using ACO-OFDM in an IM/DD system, ACO-OFDM is still more efficient in terms of power and bandwidth than OOK and PPM. ACO-OFDM also has many additional practical benefits. The ACO-OFDM subcarriers are conventional bipolar channels, and all the mature technology developed for radio communications can be applied with little or no modification. This includes techniques such as error coding, interleaving, modulation, trellis coded modulation etc. Because ACO-OFDM can tolerate large delay spreads it can be combined very easily with diversity reception and MIMO techniques. This means that the bandwidth of receivers can be increased. The limitation on the receiver bandwidth in typical optical wireless systems is set by the capacitance of the photo detector. Large area detectors are required to maximize the light energy reaching the receiver. Multiple smaller area detectors with smaller capacitances give higher bandwidths, but cannot be used with modulation techniques like PPM and OOK which are intolerant of delay spread. As a result of these many benefits ACO-OFDM is likely to be an important modulation technique for practical optical wireless systems of the future. Its application will lead to a significant increase in the data rates that can be achieved.

V. CONCLUSIONS

We have presented results for the channel capacity of intensity modulated direct detection (IM/DD) wireless optical communication systems for an AWGN channel with a limit on the average transmitted optical power. By assuming that all of the bandlimiting occurs in the receiver, we develop a mathematically tractable model which accurately represents wireless optical systems. This model is used to calculate the channel capacity of the system for two different probability distributions: an exponential distribution and a 'clipped Gaussian' distribution. For SNRs below 15dB the 'clipped Gaussian'distribution has a higher capacity, but at SNRs above 15dB the capacity of the exponential distribution is higher. The capacity of the ACO-OFDM is calculated theoretically and shown to be only slightly lower than the 'clipped Gaussian'. The loss in capacity is because the ACO-OFDM mapping results in some extra constraints on the signals. ACO-OFDM has previously been shown to be more efficient in terms of optical power and bandwidth than the modulation techniques normally used for wireless optical communications such as OOK and PPM. The results in this paper suggest that for a channel subject to the given constraints ACO-OFDM is an efficient technique in absolute as well as relative terms, and that any future modulation technique can only have slightly higher capacity. ACO-OFDM like all OFDM systems is a practical solution to multipath distortion. As most of the techniques developed for radio communications can be applied with little modification to this new scenario, ACO-OFDM is likely to be used extensively in future optical wireless systems.

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